

Preparing isomerically pure beams of short-lived nuclei at JYFLTRAP

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Abstract

A new procedure to prepare isomerically clean samples of ions with a mass resolving power of more than 1×10^5 has been developed at the JYFLTRAP tandem Penning trap system. The method utilises a dipolar rf-excitation of the ion motion with separated oscillatory fields in the precision trap. During a subsequent retransfer to the purification trap, the contaminants are rejected and as a consequence, the remaining bunch is isomerically cleaned. This newly-developed method is suitable for very high-resolution cleaning and is at least a factor of five faster than the methods used so far in Penning trap mass spectrometry.

Key words: Penning trap, isobaric separation, isomeric separation

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1. Introduction

A contamination-free ion beam is desirable for any experiment with radioactive ions. Mass spectrometry with Penning traps, where the cyclotron frequency in a strong magnetic field is determined [1], is no exception to this; contaminants do not just deteriorate the lineshapes of the obtained spectra but also introduce systematic frequency shifts.

Several purification steps are taken before the ions end up in the actual measurement stage. At the IGISOL facility in Jyväskylä [2], or at ISOL facilities in general, for instance at ISOLDE, CERN [3], a coarse mass selection is performed with magnetic separators soon after extracting ions from the ion source. Typically a mass resolving power $R = \frac{M}{\Delta M_{FWHM}} = \frac{\nu}{\Delta \nu_{FWHM}}$ from 200 to 5,000 is obtained, which is adequate for a selection of a particular mass number A , delivering a beam composed of isobars. These can be partially selected, for example, by chemical means or by selective laser ionization. A mass separation in a Penning trap requires a resolving power of 10^4 to 10^5 . Isomeric separation is more demanding: even a mass resolving power of more than 10^6 might be needed.

The JYFLTRAP system consists of a radiofrequency quadrupole (RFQ) cooler and buncher [4] and two Penning traps [5] situated inside the same 7 T superconducting solenoid. The RFQ is used for cooling and bunching of the ion beam from the IGISOL separator. Isobaric as well as isomeric separation and mass measurements are performed with the Penning traps. The first, purification trap is used for isobaric cleaning [5] and in most of the cases studied, it has been sufficient to provide contaminant-free samples for experiments. The second, precision trap is used for isomeric cleaning and high-precision mass measurements. In this article, complete purification schemes for separating isobars and close-by isomers with the JYFLTRAP Penning trap setup are presented.

2. Isobaric cleaning with the purification trap

The gas-filled purification trap is used to separate isobars by employing the sideband-cooling technique [6]. At the JYFLTRAP experiment, the following isobaric purification scheme is used:

- (i) An ion bunch from the RFQ is captured in the purification trap. The injection side potential wall is lowered for a short period of time when ions are transferred into the trap and once the ions are inside, the potential wall is restored.
- (ii) The ions are kept in the trap for 20 to 200 ms in order to let the axial and the cyclotron motion cool down.

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- (iii) A dipolar magnetron excitation is applied typically for 10 ms to establish a magnetron radius of more than 1 mm for all ions. This assures that none of the ions can be transferred through the 2-mm orifice between the traps.
- (iv) A mass-selective quadrupolar excitation with a frequency of $\nu_c = \frac{1}{2\pi} \frac{q}{m} B$ is applied. This sideband excitation at the sum frequency of both radial motions $\nu_c = \nu_+ + \nu_-$ will convert the magnetron motion of the ions into a cyclotron motion, which is much faster cooled under the presence of a buffer gas. As a consequence, the ions are mass-selectively driven back to the axis of the trap.

The achieved mass resolving power mostly depends on the buffer gas pressure and on both the duration and the amplitude of the excitation. As long as the trap is not loaded with too many ions, $R \leq 10^5$ can be obtained. An example of a quadrupolar rf-frequency scan around $A = 26$ in the purification trap is shown in fig. 1. Such a resolving power is even enough to separate the long-lived isomer ^{26m}Al from its ground state. When the purification trap is loaded with

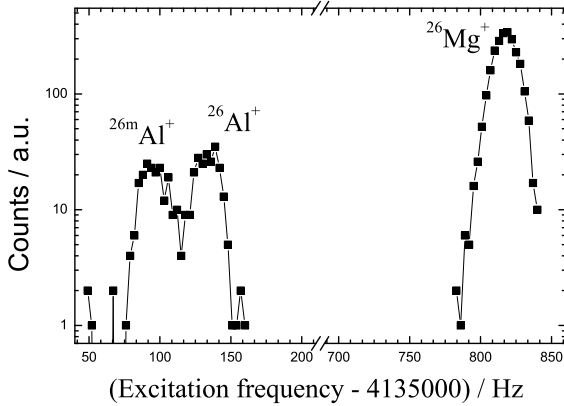


Fig. 1. Purification scan for mass $A = 26$. The excitation time that was employed was sufficient to separate the isomer and the ground state of ^{26}Al having different frequencies by approximately 40 Hz.

more ions, the trap loses its capability to efficiently bring the ions of interest back towards the axis of the trap due to increased space charge. Increasing the quadrupole amplitude and the buffer gas pressure enhances the centering process — unfortunately with expense of resolution. If the resolution is compromised (up to $\Delta\nu_{\text{FWHM}}$ of 100 to 200 Hz), the transmission of the trap can be maintained. An example of a purification scan with reduced resolution is shown in fig. 2. The isomer and the ground state of ^{54}Co are not resolved, since the difference of their cyclotron frequencies ν_c is only about 7 Hz and the trap has been tuned for better transmission at the cost of high resolution.

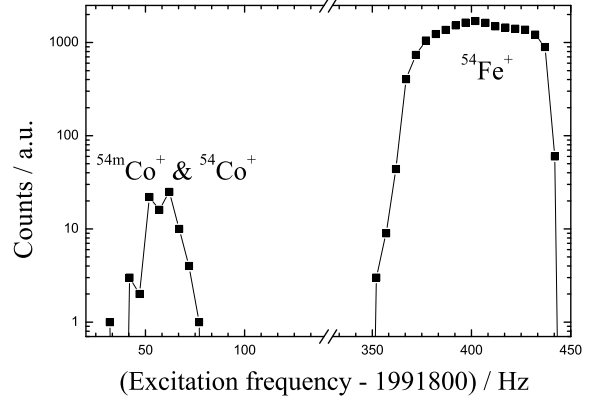


Fig. 2. Purification scan for mass $A = 54$. The isomeric and the ground state of ^{54}Co are not separated. The resolution could not be improved, since the yield of stable ^{54}Fe is overwhelming compared with the yield of ^{54}Co .

3. Isomeric cleaning with the precision trap

Since the precision trap is situated in ultra-high vacuum ($p \leq 10^{-7}$ mbar) and both the cooling and re-centering effect of the buffer gas are missing, the ion motions have to be excited differently in order to produce clean ion samples. Here, a dipolar excitation at the reduced cyclotron frequency ν_+ is typically used.

To remove contaminant ions prior to the measurement process, their radial amplitudes need to be increased such that they will not affect the ions of interest. The time profile of the excitation results in a finite lineshape in the frequency domain, given by the Fourier-transformation, where $\Delta\nu_{\text{FWHM}}$ of the resonance is determined by the time duration T of the excitation, $\Delta\nu_{\text{FWHM}} \propto \frac{1}{T}$. In addition to the normal dipolar cleaning, a Stored Waveform Inverse Fourier Transform (SWIFT) [7] can be used for a selective broadband cleaning.

3.1. Dipolar cleaning with a rectangular pulse

When using a rectangular excitation pulse, the corresponding Fourier-transformation results in a sinc function, $\sin(x)/x$, showing a characteristic sideband structure. This is not inconvenient if the frequency difference of the ion of interest and the impurity is well known. Excitation times and frequencies need to be properly set that contaminants are excited while the ion of interest is not. An excitation with a rectangular pulse is shown in fig. 3 (a). One of the frequencies for an ion of interest remaining unexcited is marked with (2). Despite all care to avoid excitation of the ion of interest, there might still be some excitation, for example due to the residual gas damping effect. On the other hand, the cleaning process with a square wave excitation is more than factor of two faster than that with a Gaussian

envelope.

3.2. Dipolar cleaning with a Gaussian envelope

By using a Gaussian envelope in the excitation time profile, the excitation pattern in the frequency domain is also Gaussian. This way, the ion of interest just needs to be sufficiently separated from contaminants in order to avoid an unwanted increase of its motional amplitudes. The resolution can be adjusted with the excitation time. This corresponds to the excitation pattern (b) shown in fig. 3. The contaminant, marked (0), is excited maximally while the ion of interest (3) remains unaffected.

This method is routinely used in many trap setups like ISOLTRAP [8] at CERN, CPT [9] at ANL and LEBIT [10] at MSU. The advantage in using dipolar cleaning is that it can be applied either in low- or high-resolution modes: Using a very short duration and a high amplitude will remove ions within a bandwidth of several kHz. Or, the amplitude can be set low and the duration long to obtain a narrow-band cleaning.

ISOLTRAP has demonstrated a selection of nuclear isomers [11] in combination with a selective laser ionisation and decay spectroscopy. Here, states of ^{70}Cu were separated with a Penning trap. In the cleaning process, a mass resolving power of about 2×10^5 was obtained with a 3-s excitation time. Although there was only one contaminant to be cleaned with the Penning trap, it should be noted that usually several contaminants are cleaned in parallel.

3.3. Dipolar cleaning with separated oscillatory fields

The resolution can be further enhanced by using an excitation scheme with time-separated oscillatory fields [12,13,14]. It has been shown that the linewidth is reduced by almost 40 % [15]. The reduction is illustrated in fig. 3, comparing the width of the main peak for (a) and (c). In case (c) the ion of interest remains unexcited at the frequency position (1). As in the case of a rectangular excitation profile, both frequencies have to be known accurately beforehand and can be conveniently used for example in measurements of superallowed beta-emitters or stable ions. This method is less suited for studying short-lived nuclides with unknown mass values.

4. Isomeric cleaning with time-separated oscillatory fields and additional cooling

In the methods introduced so far, the cleaning is performed in such a way that the contaminants are driven to orbits with large radii such that they might hit the ring electrode. To avoid excessive excitation, the ion sample can be extracted towards the purification trap: The contaminants will hit the electrode surface surrounding the 2-mm diaphragm between the traps, while the ions of interest can pass through. The remaining cleaned bunch of ions is then

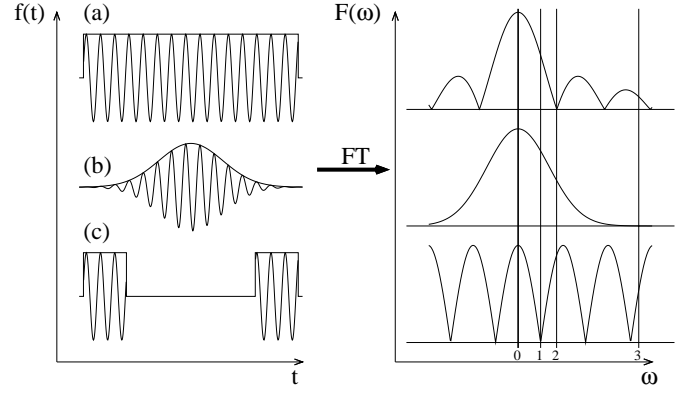


Fig. 3. Examples of excitation time profiles $f(t)$ (left side) for (a) a rectangular excitation pulse, (b) a Gauss-modulated envelope and (c) an excitation with time-separated oscillatory fields. The corresponding Fourier transformations $F(\omega)$ in the frequency domain are shown on the right. The position (0) indicates the frequency of the contaminant ion species and (1) to (3) indicate a possible frequency of an ion of interest. For the discussion see text.

captured in the purification trap, where the ions are additionally recooled and recentered as described in section 2. In this way, it is possible to perform a very-high resolution cleaning in a time-efficient manner. For instance, the mass doublet ^{115}Sn and ^{115}In has a cyclotron frequency difference of about 4.5 Hz. Using an excitation time pattern of (10-80-10) ms (On-Off-On) the different isotopes are fully separated. An example of a transmission curve after the second recentering in the purification trap is shown in fig. 4.

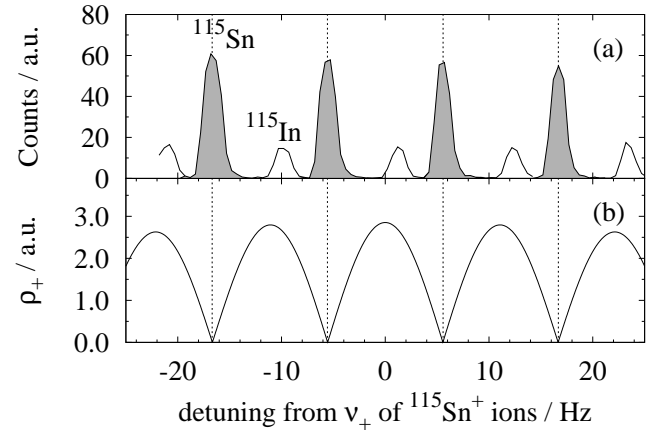


Fig. 4. Number of detected ions at the microchannel-plate detector behind the trap setup as a function of the applied dipolar frequency in the precision trap (a). Here, an excitation time pattern of (10-80-10) ms (On-Off-On) was used. Prior to their ejection the ions have been extracted backwards, captured and re-centered in the purification trap. The individual peaks are the transmitted ions of ^{115}Sn (grey) and ^{115}In (white). The lower panel (b) shows the expected increase of the cyclotron radius ρ_+ for ^{115}Sn as a function of the applied dipolar frequency. Here, the highest transmission occurs when least excited.

After a repeated centering and cooling in the purification trap the ion bunch is transferred to the precision trap for the actual cyclotron frequency determination. Figure

5 demonstrates the prospects of this cleaning procedure applied to the $A = 115$ isobars of indium and tin. If no cleaning is applied, ^{115}In is barely visible in the cyclotron resonance curve (a). The ratio between the detected ions of ^{115}Sn to ^{115}In is 5 to 1. The number can be quantified when selecting only those ions with a time of flight shorter than $350\ \mu\text{s}$, which were affected by a resonant excitation at their respective cyclotron frequency ν_c . The corresponding number of detected ions is indicated by vertical bars. In (b) ^{115}Sn was removed by a dipolar excitation at ν_+ in the precision trap, as described in section 3.3, resulting in clean resonance of ^{115}In . In (c), ^{115}In was removed in analogy to case (b).

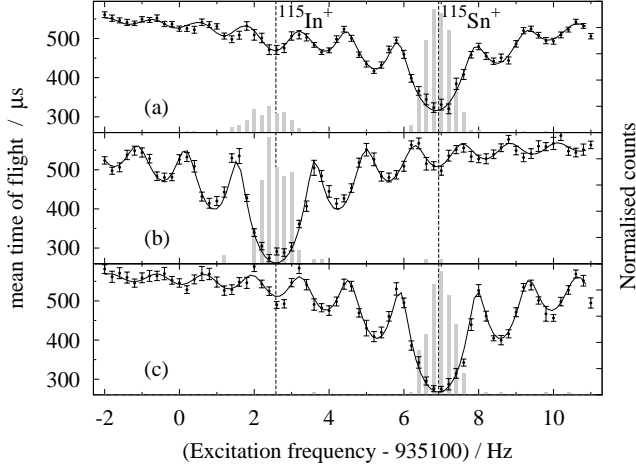


Fig. 5. Time-of-flight ion cyclotron resonances and a two-peak fit for an uncleaned ion sample (a). The ^{115}In resonance is barely visible. In the middle panel (b), ^{115}Sn has been cleaned away, which remarkably enhances the ^{115}In resonance. In the bottom panel (c), ^{115}In has been removed from the precision trap. The vertical bars indicate the normalised number of ions having a time of flight less than $350\ \mu\text{s}$.

5. Application to superallowed Q_{EC} -value measurements of ^{50}Mn and ^{54}Co

The motivation to develop a fast and universal cleaning scheme arises from a recent proposal for Q_{EC} measurements for ^{50}Mn and ^{54}Co . Both nuclides have relatively short half-lives $T_{1/2}$ of 300 ms and 200 ms, respectively. In addition, both have long-lived isomers with low excitation energies of about 200 keV. As can be seen from fig. 2, the states are not resolved with the conventional experimental sequence in the purification trap.

The fastest way of separating the ground and the isomeric state is to use dipolar cleaning with separated oscillatory fields. For the dipolar excitation, a time of 80 ms and for the repeated cooling and centering of the ions in the purification trap 100 ms are required. The resulting decay losses are about 50 %, which are counterbalanced by a rather high production rate. Examples of time-of-flight resonances are shown in fig. 6.

The excitation with separated oscillatory fields has been demonstrated to be well suited also for time-of-flight cy-

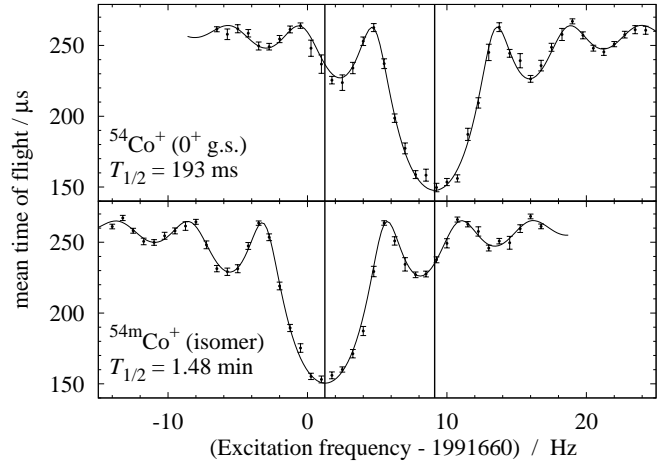


Fig. 6. Time-of-flight ion cyclotron resonances for ground and isomeric state of ^{54}Co measured in November 2006. The unwanted states have been cleaned using dipolar excitation with separated oscillatory fields. For the cyclotron frequency determination an excitation time of 200 ms was used.

clotron resonances [15]. The theoretical lineshape for fitting purposes is extensively described in [14]. Figure 7 shows an example where both the cleaning and the time-of-flight resonance were produced with an excitation by separated oscillatory fields.

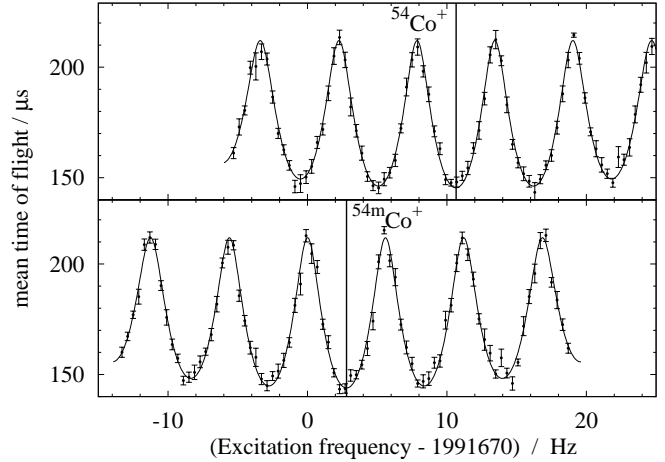


Fig. 7. Time-of-flight ion cyclotron resonances for ground and isomeric state of ^{54}Co using separated oscillatory fields for both the dipolar cleaning as well as for the cyclotron resonance measurement. A dipolar excitation pattern of (10-55-10) ms and a quadrupolar excitation pattern of (25-150-25) ms were used. The data were obtained in May 2007.

The linewidths of the cyclotron resonances shown in figs. 7 and 6 are 5.9 Hz and 3.7 Hz, respectively. In both cases a total time duration of 200 ms was spent in the excitation process. The resonances obtained with time-separated oscillatory fields are 35 % narrower. The uncertainty in the determination of the line center is reduced by a factor of 2.5.

6. Conclusions

A new high-resolution cleaning scheme employing excitation with time-separated oscillatory fields has been demonstrated. Unwanted isobaric or isomeric contaminants will be completely removed after the cleaning excitation when the ions are retransferred from the precision to the purification trap through the narrow channel. Once the cleaned ion sample has been recooled and recentered in the purification trap, the sample is ready for extraction to the experiments. Recently, this newly-developed cleaning method has been successfully used to prepare clean samples of the ground states of ^{50}Mn and ^{54}Co , where a mass resolving power of $R = 3 \times 10^5$ was needed. This cleaning method is now routinely used at JYFLTRAP to provide isomerically clean beams for experiments.

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